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Examining predation as a possible means of controlling Crown-of- Thorns Starfish (Acanthaster planci) outbreaks on reefs around Lizard Island, Australia

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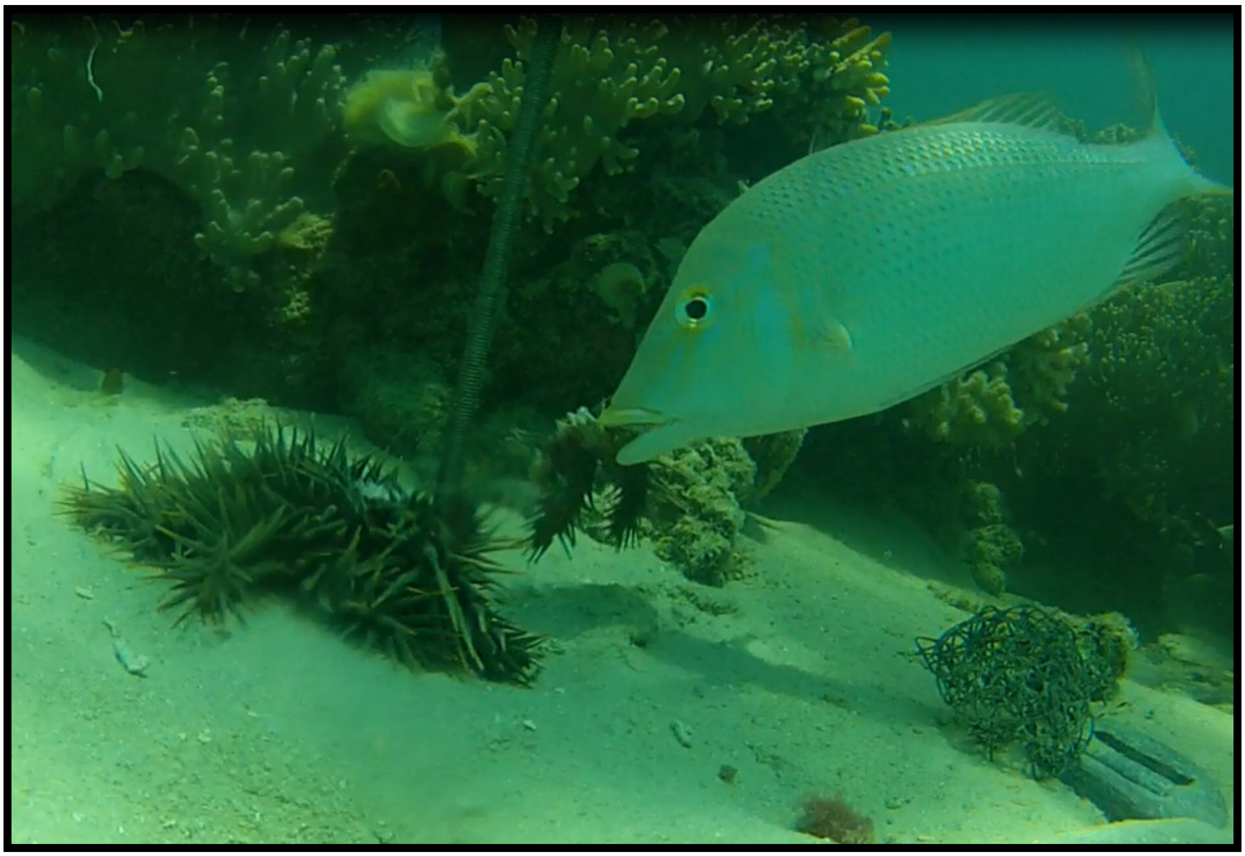

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ISP Ethics Review

ISP Ethics Review

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Abstract

Since the world's coral reefs are currently threatened by a variety of different natural and anthropogenic factors, research on protecting coral reefs is pivotal to protect these diverse ecosystems. However, only Indo-Pacific reefs such as the Great Barrier Reef are dying due to a corallivorous echinoderm threat known as the Crown-of-Thorns Starfish (*Acanthaster planci*). *A. planci* is a starfish which feeds on coral tissue and can quickly reduce coral cover on a reef during an outbreak. Although scientists are still unsure as to what causes these outbreaks, one suggestion is the predator-removal theory. The predator removal-theory states that major predators of *A. planci* are being overfished and are unable to regulate the *A. planci* population, resulting in outbreaks. This study's goal was to determine the major predators of *A. planci* in an attempt to ascertain if predation could be used to control *A. planci* populations. *In situ* predation experiments were preformed on reefs off of Lizard Island by staking whole *A. planci* on the reef with cameras to record any instances of predation. Internal organs were also put out on the reef with the whole *A. planci*, mimicking the condition of an *A. planci* after a predation event. The weight of female gonads was collected from select *A. planci* to determine the percentage of body mass composed of gonad. Overall, nine species of fish were found to consume parts of the *A. planci* and one of which (*Lethinus nebulosus*) was found to be commercially exploited. It was also determined that *A. planci* predators could be divided up into categories of "lethal predation" and "sublethal predation", with most predators of the internal organs falling under sublethal predation. Since none of the fish species that ate gonads were planktivores, it is improbable that these species are egg predators and regulate *A. planci* populations during spawning events. Finally, the percentage of mass composed of gonads increased greatly with size, stressing the importance of controlling these highly fecund individuals. Overall, future studies could continue to identify predators of *A. planci* and rates of predation of fish species on *A. planci* should be determined in order to estimate whether or not it is enough to regulate *A. planci* populations.

Keywords: *Acanthaster planci*, predation, fecundity, overfishing

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Acknowledgments

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1. Introduction

Coral reefs are some of the most diverse ecosystems on this planet and home to a wide array of different aquatic organisms, all dependent on the unique environment provided by scleratinian corals. However, these ecosystems have become increasingly threatened by a variety of different anthropogenic factors, including global warming, human development, and pollution (Pratchet et al., 2014). Even the Great Barrier Reef, considered to be one of the healthier coral reefs, may even be placed on the World Heritage danger list in the near future (Brodie 2013). While there are many different threats to the Great Barrier Reef, currently one of the main concerns is the Crown-of-Thorns Starfish (*Acanthaster planci).* For instance, over period of [37] years, *A. planci* caused a 42% loss of coral cover in the Great Barrier Reef (De'eath 2012). A single 1962 outbreak near Green Island alone destroyed 80% of the scleractinian coral (Pratchett 2005). As the quality of the Great Barrier Reef continues to decline, *A. planci* outbreaks result in further loss of coral cover, making it crucial that these asteroids be closely studied in order to protect coral reefs.

1.1. Biology and Life History of A. planci

A. planci are invertebrates, believed to exist on the Great Barrier for at least 3,000 years (Great Barrier Reef Marine Park Authority 2006). While colloquially referred to as the Crown-of-Thorns starfish, *A. planci* are easily distinguished from other starfish by their long, poisonous spines and multitude of arms (up to 21); they have even been recorded to reach sizes as large as 80 cm (Great Barrier Reef Marine Park Authority 2006; Pratchett et al., 2014). These large echinoderms live on coral reefs across the Indo-Pacific Ocean, including the Great Barrier Reef (Pratchett et al., 2014).

As a gonochoristic species, *A. planci* has separate male and female genders, identifiable by the color and shape of the gonads (reproductive organs) found along each arm (Pratchett et al., 2014). *A. planci* can live for more than five years and reaches reproductive maturity around two years old (Pratchett et al., 2014). While it still remains unclear the amount of times *A. planci* spawn during the year, spawning occurs when the water temperatures are warmer, roughly December to April (Pratchett et al., 2014). During a spawning event, *A. planci* form aggregations wherein the females release eggs and the males release sperm into the water column (Pratchett et al., 2014). *A. planci* has one of the highest fertilization successes of any invertebrate (almost 100% if the male and female are in close proximity), demonstrating how quickly *A. planci* numbers can grow and destroy a reef (Pratchett et al., 2014).

Post-settlement, juvenile *A. planci* are highly cryptic, feeding on crustose coralline algae at night until for roughly six months, afterwards switching to live coral (Pratchett et al., 2014). *A. planci* feeds upon the tissue of hard coral by exuding its stomach through its mouth (Pratchett et al., 2014). Digesting coral with stomach enzymes allows *A. planci* to consume coral up to five times faster compared to other asteroids, meaning they can also decrease coral cover much faster as well (Pratchett et al., 2014). *A. planci* preferentially feeds on *Acropora*, leaving visible feeding scars, or bleached coral, on colonies which have been predated upon.

1.2. A. planci *outbreaks*

Though recently *A. planci* have been portrayed as a malignant presence on coral reefs, the echinoderms can be an important part of the ecosystem when the numbers remain under control, naturally regulating the growth rate of coral (Pratchett et al., 2014).

However, during a large influx of *A. planci* on a reef, known as an outbreak, these starfish can wreck havoc on a reef. As Pratchett et al. (2014) highlights, there is no comprehensive definition of an *A. planci* outbreak since the conditions and population numbers a reef can healthily sustain varies. With regards to this study, a combination of outbreak definitions from Pratchett et al. (2014) and Potts et al. (1981) are be used, with an *A. planci* outbreak defined as a large aggregation on some reefs, persisting for at least several months and causing significant loss in coral cover.

A. planci outbreaks only occur in the Indo-Pacific region; Australia has had four major outbreaks in the last sixty years (Great Barrier Reef Marine Park Authority 2006). Most of these outbreaks appear to start in the Lizard Island region and extend southerly, destroying coral growth and thereby affecting the organisms which rely on coral reefs for resources (Great Barrier Reef Marine Park Authority 2006). During an outbreak, *A. planci* diversifies the species of coral consumed due to increased competition for resources (Pratchett et al., 2014). Not only is fast growing *Acropora* consumed, but also slow growth *Porites* colonies and many other coral species which take much longer to recover from *A.planci* damage than *Acropora* (Great Barrier Reef Marine Park Authority 2006; Pratchett et al., 2014).

1.3. The predator-removal theory

With four recorded outbreaks on the Great Barrier Reef, scientists are trying to determine whether these *A. planci* outbreaks are caused by natural or anthropogenic factors. Three major hypotheses suggested are the natural occurrence theory, the increased nutrients theory, and the predator removal theory (Pratchett et al., 2014). The natural hypothesis suggests normal fluctuations in the environment result in the concurrent fluctuation of A. planci numbers. Contradictorily, the second hypothesis believes *A. planci* outbreaks are caused by anthropogenically increased nutrient levels in the water from sediment run-off.

Research on predation of *A. planci* is driven by the third hypothesis, the predator-removal hypothesis. The predator removal hypothesis states that *A. planci* populations are naturally regulated by predation of adult and juvenile *A. planci* by fish and invertebrates (Pratchett et al., 2014; Rivera-Posada et al., 2014). Overfishing of these predators may result in fewer organisms regulating the *A. planci* population and, free from pressures of predation, the highly fecund *A. planci* are able to increase their numbers and rapidly take over the reef. Major recorded predators of *A. planci* include emperors, pufferfish, triggerfish, humphead maori wrasse, and giant triton snails (Rivera-Posada et al., 2014; Pratchett et al., 2014). These predators are known to target the energetically-rich digestive organs: the pyloric caeca (commonly known as "gills") and the poison-containing reproductive organs (gonads) (Rivera-Posada et al., 2014).

In support of the predator-removal hypothesis, Rivera-Posada et al. (2014) found that *A. planci* collected from no-take marine reserves (which forbid fishing) had the most damage compared to other *A. planci* collected from unprotected areas. In 2008, Sweatman also concluded that there are less *A. planci* outbreaks in no-take zones but could not definitively explain the reason behind this occurrence. As such, a lot of research involving predation on *A. planci* remains uncertain as to what degree predation actually plays in regulating *A. planci* populations (Pratchett et al., 2014). However, there has been extensive modelling which suggests that rates of predation can still be enough to regulate *A. planci* numbers (Rivera-Posada et al., 2014).

A similar study to the current study (S. Gabriel, unpubl.) was conducted on the same reef off Lizard Island this past year. While it was apparent that A. planci were disappearing because of predation within 24-28 hours of being placed on the reef, no instances of predation were caught on camera (S. Gabriel, unpubl.). However, it established that there are unknown predators present on this reef that engage on predatory behaviour towards *A. planci* (S. Gabriel, unpubl.).

Currently, the main method of controlling *A. planci* during an outbreak is injecting individuals with sodium bisulphate or a combination of oxbile and oxgall (Pratchett et al., 2014). However, these methods are both time consuming and costly, requiring divers to inject every individual *A. planci* observed on a reef. As a result, scientists have attempted to come up with alternative methods of *A. planci* population control, hence the advantages of the predator removal theory. If major predators of *A, planci* are identified and currently threatened by the fishing industry, scientists can work with fisherman to ensure these predators are not overfished and can continue to naturally regulate *A. planci* populations.

1.4. Study Objective

This study aims to determine the main predators of *A. planci* in different life stages and conditions on a reef near Lizard Island *in situ* in attempts to see if predation is a feasible method of controlling *A. planci* populations. Live *A. planci* were staked on a reef off the coast of Lizard Island and filmed over the course of three weeks in order to ascertain the predators of adult *A. planci*. Pyloric caeca and gonads were also filmed *in situ* to simulate damaged *A. planci* and establish the organisms which consume the inner organs of *A. planci* after a predation event has occurred. Since these two organs are purported to have different toxicities, trials with the pylorica caeca and gonads will also determine if fish preferentially eat organs based on their toxicity. The *in situ* gonad trials also served the alternative purpose of figuring out potential egg predators during *A. planci* spawning events. Before being placed out in the field, volume and weight of female gonads were also be collected in order to more accurately predict the percentage of body mass composed of gonads of female *A. planci* in relation to their size. From the data collected, this study strives to obtain new information regarding *A.planci* predation in order to better control *A. planci* outbreaks.

2. Materials and Methods

Fig 1. Map showing the location of reef where research was conducted on Lizard Island, Australia. Map courtesy of Google Maps.

2.1. Study Site

All *in situ* research for this study took place on the reef in front of the research station off the western coast of Lizard Island, Australia (4°40.056′S, 145°27.744′E). At a depth of roughly two meters, these shallow reefs are roughly 200 meters from the shore (Fig 1).

2.2. Collection Methods

43 *A. planci* were collected from various reefs around Lizard Island (Watson's Bay, Vicki's Lagoon, Horseshoe Bay, out front of Casuarina Beach, South Palfrey,

Mermaid Cove, South Island). Specimens were collected manually with the assistance of either metal hooks or tongs and then transported back to the Lizard Island Research Station by boat in nally bins filled with salt water. At the Lizard Island Research Station aquarium, *A. planci* were housed in three 500 ml tubs in the aquarium that were constantly supplied with salt water. While kept in captivity, no food was given to the study organisms and tanks were cleaned whenever water became murky in order to minimize *A.planci* deaths in captivity.

2.3. Dissection methods

Including *A. planci* used for a long term study on fecundity, a total of 38 *A. planci* were dissected. Prior to each dissection, the diameter of each *A. planci* was taken at two 90˚ axes by way of a measuring board. The weight, total number of arms, and arms missing were also noted. With the use of a scalpel, dissection scissors, and tweezers, *A. planci* were dissected by removing the top layer of skin, exposing the internal organs and skeleton.

The pyloric caeca, brown gill-looking organs, were collected from the middle of each arm, two per arm (Fig. 2). These were then collected and weighed. The gonads found between and on each arm of *A. planci,* were only collected from female *A. planci* (Fig 2). Females were determined visually by the gonads; female gonads are yellower and release eggs when placed in freshwater. Gonads were then weighed and the volume was determined by use of a graduated cylinder. After dissection was completed and the aforementioned measurements were recorded, gills and gonads were frozen separately in plastic cups in order to kill the eggs and make transportation of these organs easier for the *in situ* trials. The bodies of the dead *A.planci* were buried above the high tide mark on Casuarina Beach.

Fig 2. A dissected female *A. planci*, showing the relative location of the pyloric caeca (gills) and the gonads

2.4. In situ *predation*

13 whole *A. planci* were used for the *in situ* predation trials over the course of 17 days, 11 of which were live adults, one was a juvenile, and one was dead prior to the trial. Before the trial, for the majority of the *A. planci* used, the diameter, weight, tube feet, spines, and gonad sample were collected. *A. planci* were then transported out to the study site in a bucket filled with salt water on the back of a kayak. Once at the site, the *A. planci* was placed on the flat soft substrate right in front of the reef edge and secured to this area by hammering a metal pole through the oral disc. Two *A. planci* were staked out on a reef at a time for the first three days of the experiment until the malfunction of the Go Pro Hero 3 made this impossible. Then, for the remaining

14 days, one *A. planci* was staked out on the reef at a time and replaced when it disappeared.

Each trial consisted of 1 *A. planci* and possibly one gill and one gonad packet (depending on the trial) filmed by a Go Pro zip tied to a dive weight (Fig. 3). Due to transportation issues, the gills and gonads were placed out on nine of the 13 trials. Prior to transportation, the internal organs were each wrapped in mesh netting with holes large enough for fish to eat the organs. These “packages” were then zip tied to a dive weight to weigh them down. Prior to transportation, the packages were placed separately into plastic bags to minimize leakage of the organs during the journey to the site.

The Go Pro was placed roughly an arms length from the *A. planci* in order to record any instances of predation. Originally, four Go Pros (3 Go Pro Hero 2s, and 1 Go Pro Hero 3) were used in rotation for the predation trials. After the malfunction of the Go Pro Hero 3, only the Go Pro Hero 2s were used for the rest of the study. Go

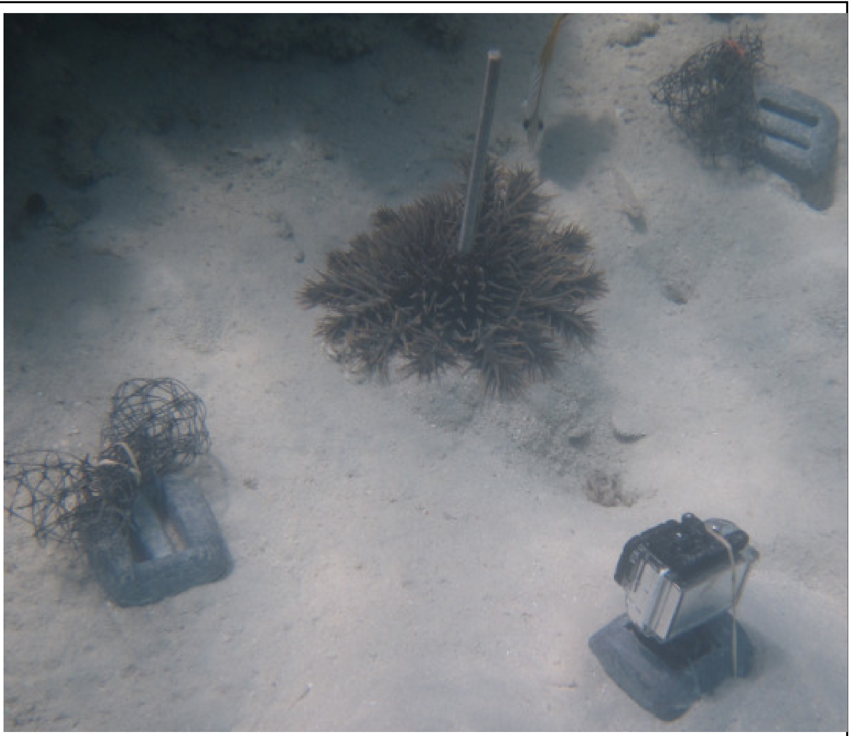

Fig 3. The *in situ* predation set-up consisting of a live *A. planci*, gill and gonad packets, and a Go Pro at the edge of the reef.

Pros were numbered so details such as the date, time, identity of *A. planci* filmed, and identity of internal organs was kept track of when videos were later downloaded.

A. planci and the internal organ packets were placed out on the reef and Go Pros filmed in the morning (~ 8:30) and the early afternoon (~13:30) for as long as the battery would last. On a full battery, Go Pros recorded footage for roughly four hours. A new Go Pro was used for the morning filming and the afternoon filming and then the Go Pro was collected at around 16:00. In five of the trials, a Go Pro was left out at ~16:00 and collected the next morning to see if any predation occurred during twilight or at night. Two of these five trials used a dive lamp in order to clearly see the *A. planci* at night.

2.5. Data Analysis

Each of the videos were analysed for instances of predation and predators were identified to the species level with the help of fish identification guides such as the online Lizard Island Research Station Field Guide and the *Reef Fish Identification: Tropical Pacific* book. Bite rate was also calculated for each species in all of the videos. Since many of the videos ran for different time lengths, they were standardized by watching 90 minutes of each video and excluding the videos that were shorter than 90 minutes. This resulted in a total of eighteen videos used for the bite rate average.

Qualitatively, the major feeding/predation behaviours of each species were also noted. These involved either behaviours which mutilated *A. planci,* such as ripping off an arm, feeding which did not noticeable alter the appearance of the *A. planci,* such as picking on the outside surface. Feeding behaviours were divided up into five categories: picks at whole *A.* planci, mutilates *A. planci,* feeds on *A. planci* debris, feeds on pyloric caeca, and feeds on gonads. The feeding behaviour of picking at whole *A. planci* usually involved fish picking at the exterior of the whole *A. planci* without causing visible damage. If fish caused visible damage to *A. planci*, such as ripping off a limb, it was classified under "mutilates *A. planci*". Feeding upon the ripped off limbs or exterior of *A. planci* after a predation was classified as "feeds on *A. planci* debris". If fish were seen to feed from the gill or gonad packets, this feeding behaviour was classified as "feeds on pyloric caeca" or "feeds on gonads".

Fecundity across size classes was estimate by plotting average diameter of *A. planci* against the percentage of mass composed of gonads. For each female *A. planci* dissected, the gonad weight was divided by the total mass to get the percentage of gonads. All data was calculated and graphs were formed by way of Excel.

3. Results

3.1. In situ *predation*

13 *A. planci* were placed out on the reef and all disappeared, most likely due to predation. 12 *A. planci* were eaten within 24 hours of being placed on the reef; the 13th *A. planci* (the dead one) was taken within 18 hours. Usually after an *A. planci* disappeared fragments of *A. planci* such as spines were left over, suggesting that predation had indeed occurred. In some cases, even whole arms were left scattered around the reef.

Overall, a total of nine species partook in

Fig. 4 Spine fragments of *A. planci* as a result of a possible predation event.

Table 1. Nine species of fish observed feeding on *A. planci* with the five common feeding behaviour categories listed qualitatively. "X" indicates the species was not observed performing this feeding behaviour and "√" indicates the species was observed performing the feeding behaviour.

Species	Common Name	Picks at whole *A. planci*	Mutilates *A. planci*	Feeds on *A. planci* debris	Feeds on pyloric caeca (gills)	Feeds on gonads
Chaetodon auriga	Threadfin butterfly fish	√	X	√	√	X
Lethrinus nebulosus	Spangled emperor	√	√	√	√	√
Scolopsis billneata	Two-line monocle bream	√	X	√	√	√
Dischistodus perspicillatus	White damselfish	√	X	√	√	√
Halichoeres. chloropterus	Pastel-green wrasse	√	X	√	√	√
Thalassoma. lunare	Moon wrasse	√	X	√	√	√
Cheilinus chlororus	Floral Maori wrasse	X	X	√	√	X
Arothron stellatus	Starry pufferfish	√	√	√	√	√
Pomacanthus. sexstriatus	Six-bar angelfish	√	X	√	X	X

feeding/predatory behaviours directed towards the whole *A. planci* or the *A. planci* debris that were left after a predation event (Table 1). Feeding behaviour differed depending on the species, with some preferring the whole *A.* planci while others preferred fragments. Some species, such as *C. chlororus*, fed mainly on the gills while other species like *A. stellatus* liked to feed on the whole *A. planci*. *A. stellatus* was the one species seen most frequently to eat a whole, live *A. planci*. *L. nebulosus* was the only other species that caused observable damage to *A. planci*, the rest mainly picked on the outside or at the internal organs.

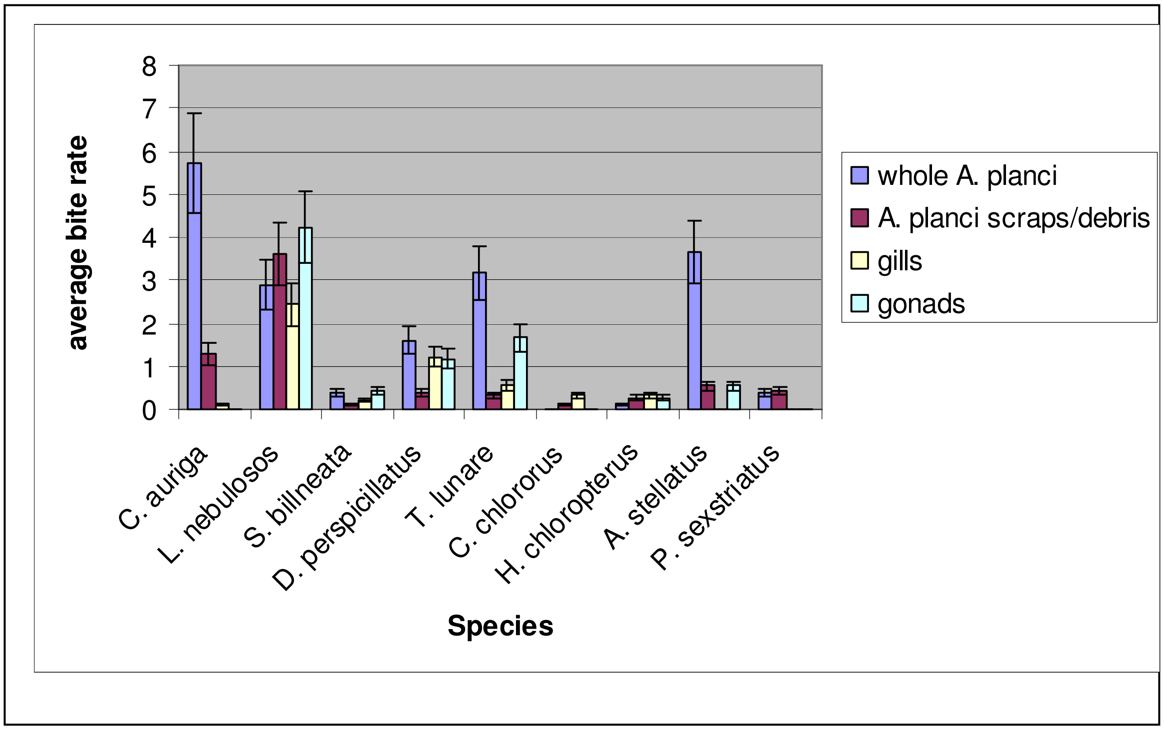

Fig 5. Average bite rate of all of the fish species observed feeding upon the whole A. planci, scraps, or the gills and gonads. Average was calculated over the total of 18 videos.

Among the nine different species, bite rates differed depending on what part of the *A. planci* was consumed, either the whole *A. planci, A. planci* debris, the gills or the gonads (Fig. 5). Some species, like *C. auriga*, had the highest average bite rate on the whole *A. planci* while other species such as the *L. nebulosus*, had the highest average bite rate at the gonads. Within a species, a higher bite rate was interpreted to imply preference of one part of the *A. planci* over another.

3.2 Female A. planci *fecundity*

When looking at fecundity of female *A. planci*, it appears that the percentage of female *A.planci* mass composed of gonads grows almost exponentially with the diameter

(Fig. 5). More than 20% of the largest female's mass is composed of gonads. On the other hand, a smaller female's weight is less than 5% composed of gonads.

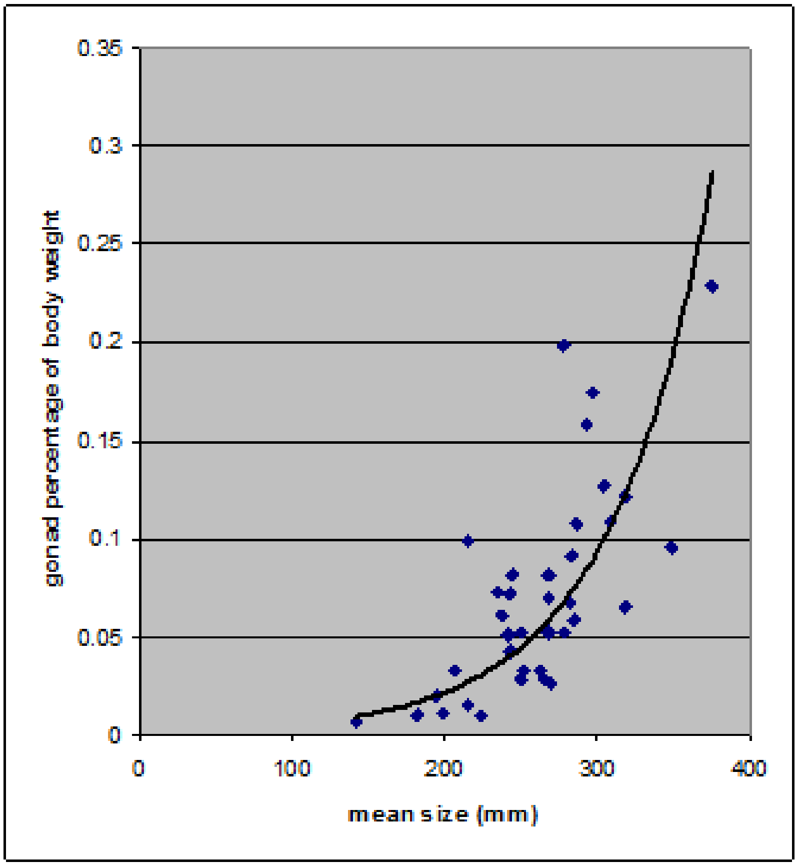

Fig 6. The size of female A. planci in relation to the proportion of gonad mass to body mass. Fitted with an exponential trendline.

4. Discussion

4.1 The predator-removal hypothesis: applicable to A. planci *predators observed in this study?*

Overall, it appears that all the whole *A. planci* used in the *in situ* predation experiment were a subject of predation, with the majority disappearing within 24 hours (Fig. 4). This high rate of predation may in part be due to the fact that *A. planci* were staked on an exposed reef flat, making it easy for predators to find these echinoderms that usually hide under coral.

Regarding bite rate, *C. auriga*, while possessing the most average bite rates to the whole *A. planci*, did very little noticeable damage to *A. planci*. Other species such as *S. billneata, D. perspicillatus, T. lunare, C. chlororus, H. chloropterus, and P. sexstriatus,* were observed to consume mainly scraps or the gills and gonads (Fig. 5). The predators that caused the most visible damage to *A. planci* were *A. stellatus* and *L. nebulosus* (Table 1).

In context of the predator-removal hypothesis, *A. stellatus* harmed *A. planci* the most, even killing a few in select cases (Table 1; Fig. 5). This fish appears to be a likely candidate as an *A. planci* predator which could potentially regulate *A. planci* populations. However, this fish is not known to be commercially exploited so the predator-removal hypothesis does not appear to apply in this case (Sweatman 1995). On the other hand, the *Lethrinidae* family (consisting of *L. nebulosos)* are exploited commercially (Sweatman 1995). So, one of the major predators observed on Lizard Island reefs does fit the requirements of a predator under the predator-removal hypothesis and it is possible that the protection of this species has the potential to better regulate the *A. planci* population and subsequently prevent *A. planci* outbreaks.

Even if only *L. nebulosus* is the only commercially exploited fish observed to feed upon *A. planci*, this does not mean that the other eight species of fish observed to feed upon *A. planci* are not indirectly affected by overfishing. One cannot rule out the possible influence of trophic cascades on these species (Dulvy et al., 2004**).** Sweatman (1995) suggest that no-take zones in the Great Barrier Reef may increase numbers of piscivores that way of trophic cascades also increase invertebrates which prey on *A. planci***.** While *A. stellatus, S. billneata, D. perspicillatus, T. lunare, C. chlororus, H. chloropterus,* and *P. sexstriatus* in particular may not be overfished, the overfishing of larger benthic predators may in turn affect the abundance of other species of fish.

4.2. Different feeding behaviours of species on whole A. planci

While there were a variety of species of fish that fed on the whole *A. planci*, they did not all cause equal amounts of damage (Table 1). For instance, *C. auriga* has the highest average bite rate of all the species seen feeding on the whole *A. planci* (Fig. 4). However, *L. nebulosos* and *A. stellatus* caused the most visible damage to *A. planci* (Table 1). While bite rate may be used successfully in determining major predators of other marine species such as dolphins, in the case of *A. planci*, bite rate may not always been an accurate method of determining major predators (Heithaus et al.,2006). If one were to look at bite rate alone, it would appear that *C. auriga* would be an important predator and cause a lot of damage when, in reality, *A. stellatus* is the most likely species in this study to kill *A. planci*. So when considering main *A. planci* predators and conservation of these predators, it would be necessary to look not only at bite rate, but also at actual feeding behaviours as well.

As the potential effect these species may have on *A. planci* depends on its feeding behaviour, it is important for one to highlight these differences. In Pratchett (2014), *A. planci* predators were distinguished as ones that "prey on live starfish", and "capacity to kill". Within the framework of study, it appears that predators of *A. planci* can be divided into two categories: lethal predators which can cause potentially life-ending damage and sublethal predators that mainly pick at the outside surface or the gills and gonads. *L. nebulosos* and *A. stellatus* fall into the former and *C. auriga* into the latter. While the lethal predators cause the most visible damage to *A. planci,* sublethal predators can also play an important part of regulating *A. planci* population dynamics by diverting energy away from reproduction to healing (McCallum et al., 1989).

4.3. Mimicking predation of injured A. planci

There were quite a few species of fish that ate the gills and gonads; many of those never caused any apparent damage to healthy *A. planci* (Fig. 5; Table 1). It also became apparent from the videos that the combination of the gill and gonad packets attracted more fish to the area in general. Glyn (1984) also saw a similar occurrence, with more fish coming to an area after an *A. planci* had been damaged and its organs were exposed. In the instance of a non-lethal predation event, an injured *A. planci*, with its exposed gills and gonads (mimicked by the gill and gonad packets), has the potential to attract more fish to the area. Fish attracted to this mutilated starfish could then result in even more (possibly lethal) predation since it has been reported that the attack rate of mutilated star fish is higher than that of a non-mutilated starfish (McCallum et al., 1989).

Even if the mutilated starfish was not killed by predation, injured *A. planci* may be less fecund after an attack since there are fewer gonads present or more energy has to be put towards repairing the arm instead of reproduction (McCallum et al., 1989; Rivera-Posada et al., 2014). While they may not mutilate or destroy *A. planci,* species which consume gills and gonads can still play a role in regulating *A. planci* population by redirecting the *A. planci*'s energy away from reproduction. In essence, these are sublethal predators, causing reduced fecundity in *A. planci*. Less reproductive energy means the potential for less *A. planci* eggs released during spawning and less of a chance for fertilization.

4.4. Predation of gonads as a means of determining egg predation

In an attempt to ascertain potential predators of *A. planci* eggs the gonad packet study was performed. Six species (*Lethrinus nebulosus, Scolopsis billneata, Dischistodus* *perspicillatus, Thalassoma lunare, Halichoeres. chloropterus,* and *Arothron stellatus*) were observed to consume the gonads (Fig. 5). While it has been suggested that some fish may avoid *A. planci* eggs since they contain saponins (an inflammatory vvnom), the results of this study suggests saponins may not be as strong a deterrent for egg predators as previously believed (Lucas et al., 1979). These six fish species were seen trying to eat the gonads through the mesh, sometimes even biting through the mesh. In fact, *L. nebulosus* actually had the highest average bite rate with the gonads (Fig. 4). This is quite surprising since planktivores are usually the main consumers of gonads/eggs during spawnings (Lucas et al., 1979). However, in aquarium experiments, Rivera-Posada et al. (2014) observed two species of triggerfish that were not planktivores consuming the gills and the gonads as well. It was also noted that fish that would not usually ate gonads would consume them from a damaged *A. planci* (Glyn 1984). Perhaps consumption of gonads is a more common behaviour among other feeding groups of fish when the *A. planci* gonads are in clumps versus spread out during spawning.

Observing *A. planci* egg predation in the field is a rarity and as such there is very little information on predators of *A. planci* eggs. In a list of 27 species that consume *Acanthaster*, only *Abudefduf curacao* was observed to prey on eggs (Pratchett et al., 2014). Field observations of these species are needed to confirm whether or not the six species are truly egg predators. However, since none are planktivores, it appears unlikely that any of these species would be egg predators during spawning events.

4.5 Implications of the highly fecund A. planci

The percentage of female mass composed of gonads appears to increase exponentially with size (Fig. 6). These findings are supported by previous studies which also recorded fecundity increasing disproportionately with the diameter of female *A. planci* (Pratchett et al., 2014; Kettle and Lucas 1987). The drastic amount of energy *A. planci* puts into fecundity really highlights how hard it is to regulate *A. planci* populations, especially during an outbreak. With fertilization close to 100% when males and females are in close proximity, a single female could potentially release millions if not billions of eggs onto the reef in one year (Pratchett et al., 2014). With the sheer amount of energy devoted solely to reproduction, the role of potential predators of *A. planci* larvae and eggs during spawning events and recruitment becomes quite important, especially since scientists have yet to determine the exact times when *A. planci* spawn and as such cannot prevent these spawnings (Pratchett et al., 2014).

4.6 Conclusions

Overall, this study determined there are at least nine species of fish living on the Great Barrier Reef near Lizard Island that prey on and even possibly kill *A. planci*. While at this time it cannot be definitively proven that the predator removal hypothesis is a major factor in *A. planci* outbreaks, this study has shown there are species of fish on the Lizard Island reefs which have the potential to regulate *A. planci* populations. The frequent occurrence of predation events directed towards *A. planci* also shows that *A. planci* predation of appear to be an important process on Lizard Island reefs.

Future experiments should once again look at predation of *A. planci* but in a setting that does not expose it in an unnatural manner, such as under coral. It would be also beneficial to look at predation at a variety of reefs around Lizard Island, not just the one reef this study was centred no. Since most of the reefs around Lizard Island are no-take zones, it would be interesting to compare the rates of predation and abundance of *A. planci* on the reefs around Lizard Island to unprotected reefs, in a similar method to Dulvy (2004). Another logical next step would be to determine whether or not rates of predation at Lizard Island on adult *A. planci* and *A. planci* eggs are enough to actually regulate *A. planci* populations. Models have established that it is feasible for a large enough predator community to regulate *A. planci* populations (Pratchett et al., 2014). However, as McCallum (1989) points out, if there are a high number of recruits or movement to a reef, it is possible that predators could not continue to regulate the population, even if they were doing so beforehand.

It appears that predators of *A. planci* are more like a buffer against outbreaks; they may not be able to prevent an outbreak once it has started (McCallum et al., 1989). Considering this fact, if the predator-removal theory does apply to *A. planci* outbreaks, major predators of *A. planci* should be under protection at all times, not just during the onset of an outbreak. This highlights importance of marine reserves and no-take zones as possible methods of regulation. Implementing these reserves at certain reefs would allow *A. planci* predators, both lethal and sublethal, to be protected at all times. In order to truly control these *A. planci* outbreaks in the future, scientists must continue research on the ultimate cause of these outbreaks, making research on hypothesis such as the predator-removal hypothesis extremely important. Only after the ultimate cause is discovered can the Great Barrier Reef be fully protected from these outbreaks.

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